ROLE OF DISTRIBUTED INTER-BRISTLE FRICTION FORCE ON BRUSH SEAL HYSTERESIS

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Introduction and Background

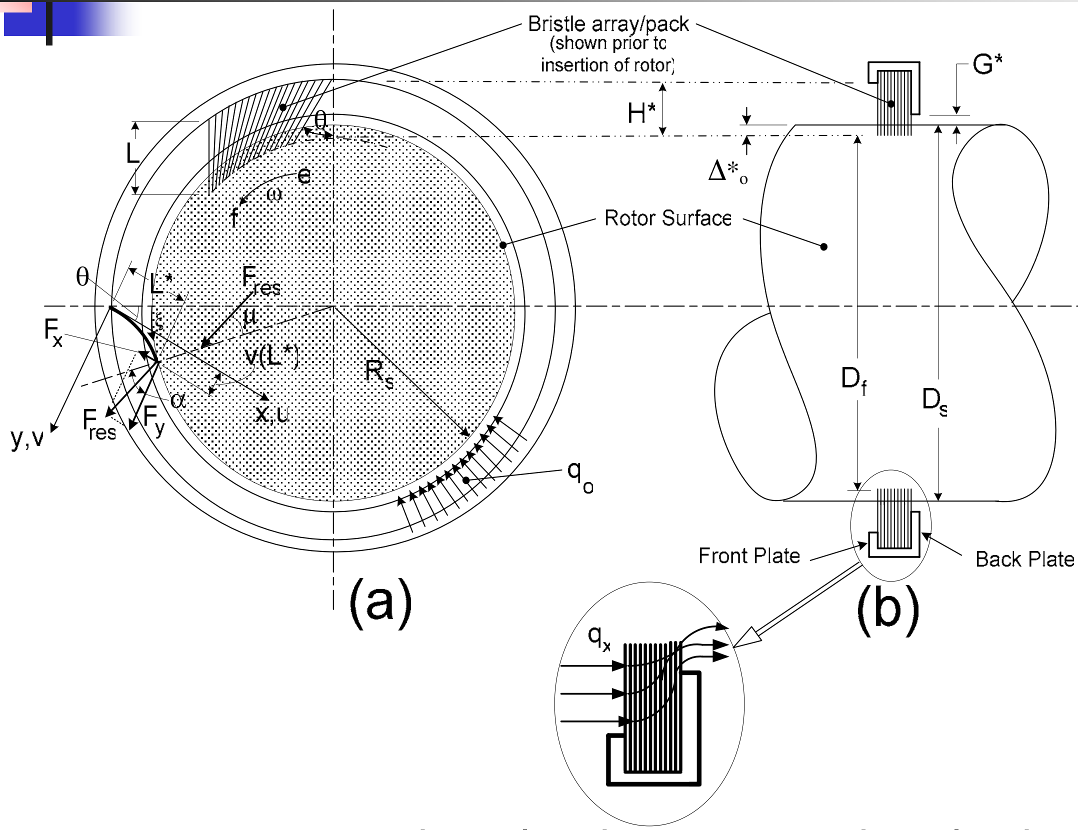

Figure 1 Brush seal with various working loads

Figure 1

- Interference parameter Δ^*_o
- Inward radial flow-induced load q_o
- Contact force F_{res} generated at interface of fiber tip and rotor
- Local oncoming flow of gas toward bristle pack q_x

Inter-bristle friction force model

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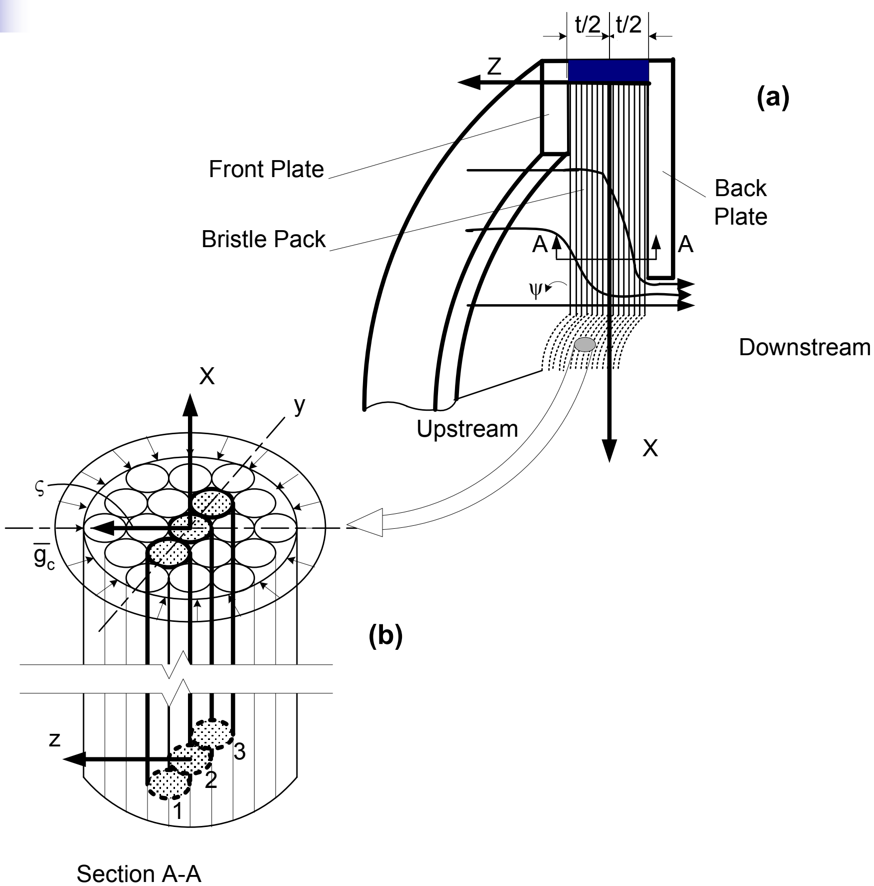

Figure 2

(a) Depiction of partial brush seal with front and back plate that constrain bristle pack

(b) Section A-A view, depicting the compactive load g_c around bristle pack. The interactive forces of three fibers (1, 2, 3) are studied for hysteresis phenomenon

Inter-bristle Friction Model (cont'd)

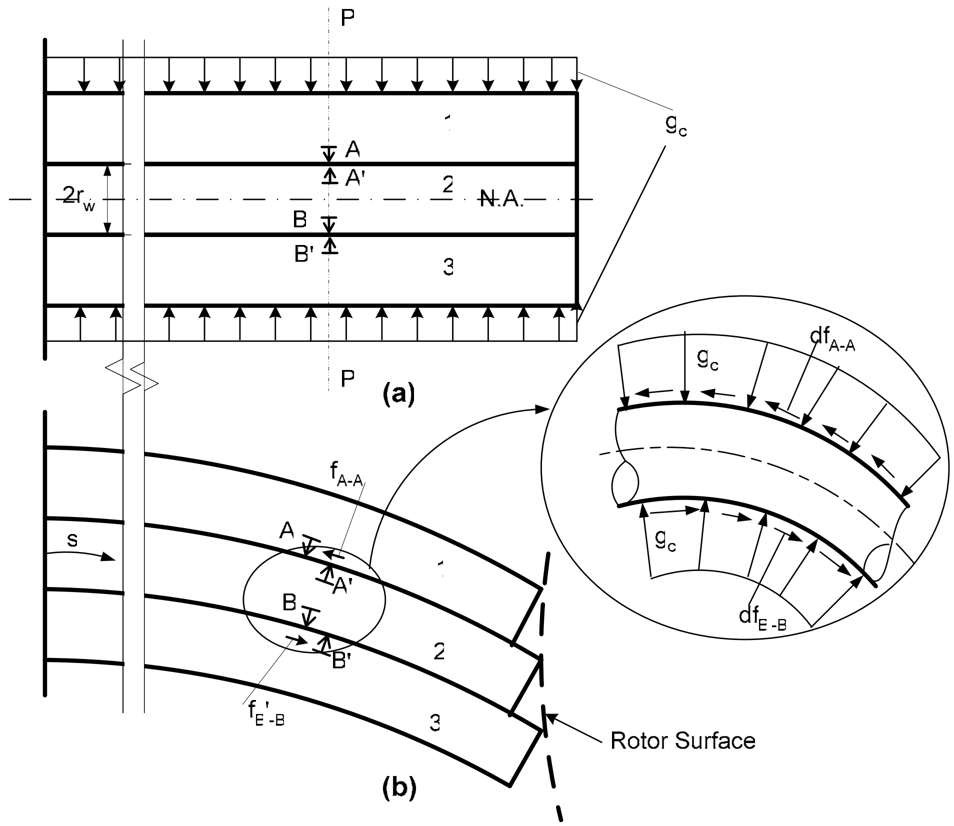

Figure 3

- Three un-deformed neighboring fibers subjected to the compactive load g_c
- Deformation of fibers under compactive load g_c.

Inter-bristle Friction Model (cont'd)

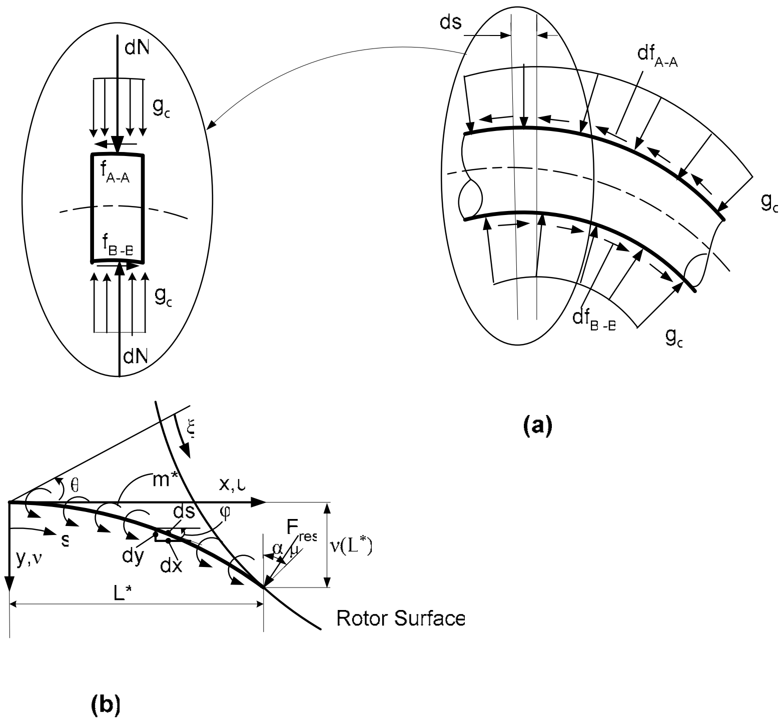

Figure 4

(a) Segment of the deformed fiber subjected to the uniform compactive load g_c and traction force $f_{A\text{-}A'}$ and $f_{B'\text{-}B}$

(b) simplified model depicting interaction between neighboring bristles as uniformly distributed moment m* along deformed fiber

Inter-bristle Friction Model---derivation of m*

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Refer to Fig.3 and Fig.4:

1. Differential frictional force $df_{A-A'}$ and $df_{B'-B}$

$$\left.\begin{array}{l} df_{A-A'} = \mu dN; df_{B'-B} = \mu dN \\ dN = ds \cdot g_c \end{array}\right\} \Rightarrow \begin{array}{l} df_{A-A'} = \mu g_c ds \\ df_{B'-B} = \mu g_c ds \end{array}$$

2. Differential moment dm:

$$dm = 2\mu g_c r_w ds$$

3. Resisting bending moment m

$$m = 2\mu g_c r_w L$$

4. Distributed bending moment per unit length m

$$m^* = 2\mu g_c r_w$$

If Hexagaonal closed-pack, then $m^* = 2\mu g_c r_w (1 + 2\cos 60)$

Governing Equation

According to Euler-Bernoulli Law:

$$EI\kappa = M_{m^*} + M_{F_{res}} \quad \text{with} \quad \kappa = \frac{d\phi}{ds}$$

Governing Equation:

$$EI\frac{d^2\phi}{ds^2} = m^* - F_{res}\cos(\alpha - \mu - \phi)$$

Non-dimensional form of governing equation:

$$\frac{d^2\phi}{ds^{*2}} = \frac{m^* H^{*2}}{EI} - \frac{F_{res} H^{*2}}{EI}\cos(\alpha - \mu - \phi)$$

Boundary conditions and constraint conditions

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Boundary conditions:

1. slope constraint at the bristle origin, i.e.

$$\Phi=0 \text{ at } s=0$$

2. Free of moment at the bristle tip, i.e.

$$d\Phi/ds=0 \text{ at } s=L$$

Constraint conditions:

$$\left|x_t - x_\xi\right| < \varepsilon; \left|y_t - y_\xi\right| < \varepsilon$$

Where,

$$x_t = \int_0^L \cos\phi ds; \; y_t = \int_0^L \sin\phi ds$$

$$x_\xi = (R_s + H^* - \Delta_o^*)\cos\theta - R_s\cos(\theta + \frac{\xi}{R_s})$$

$$y_\xi = R_s\sin(\theta + \frac{\xi}{R_s}) - (R_s + H^* - \Delta_o^*)\sin\theta$$

Eccentricity of Shaft

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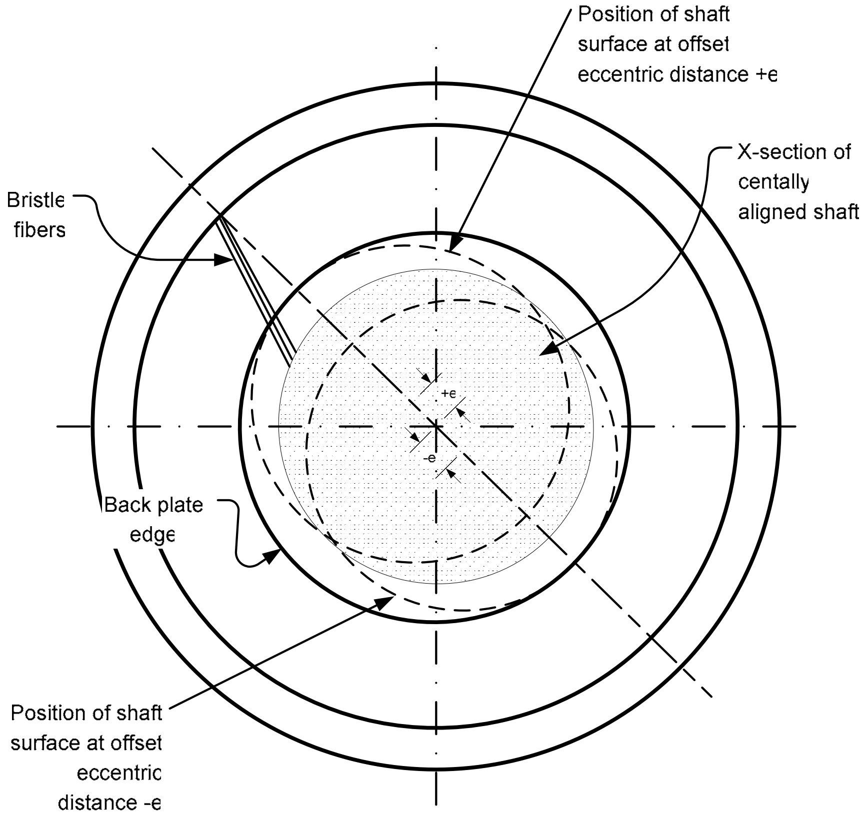

Figure 5

Eccentric movement of rotor and displacement of bristle pack

Numerical Results and Discussion

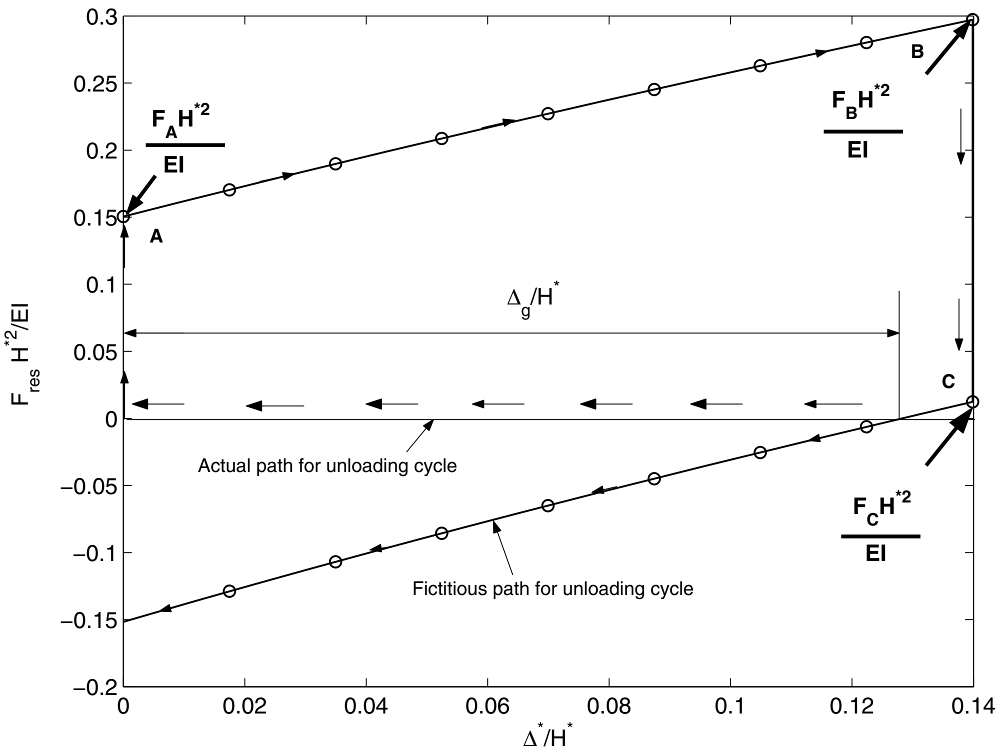

Figure 6

Relationship between $\frac{F_{res} H^{*2}}{EI}$ and $\frac{\Delta^*}{H^*}$ during loading and unloading Δ^* for a transition seal with R_s/H^*=8.9, θ=45[0] and $\overline{m} = \frac{m^* H^{*2}}{EI}$=0.135.

Δ_g/H^* shows the position where fibers are "stuck", i.e., cannot completely recover from bending during unloading Δ*

Numerical Results and Discussion (Cont'd)

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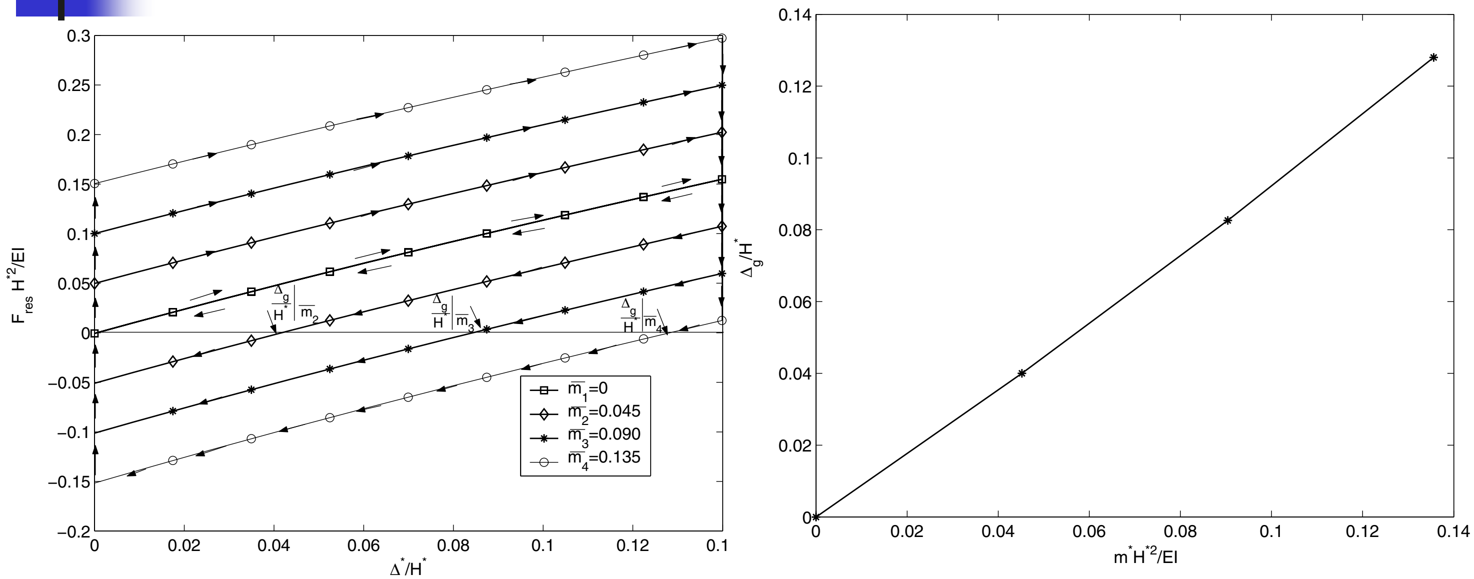

Figure 7 (a) Relationship between dimensionless contact force and dimensionless penetration depth for $\overline{m}$ =0, 0.045, 0.090, 0.135. (Results shown are for R_s/H^*=8.9, θ=45º; (b) relationship between Δ_g/H^* and non-dimensional bending moment $\overline{m}$

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Numerical Results and Discussion (Cont'd)

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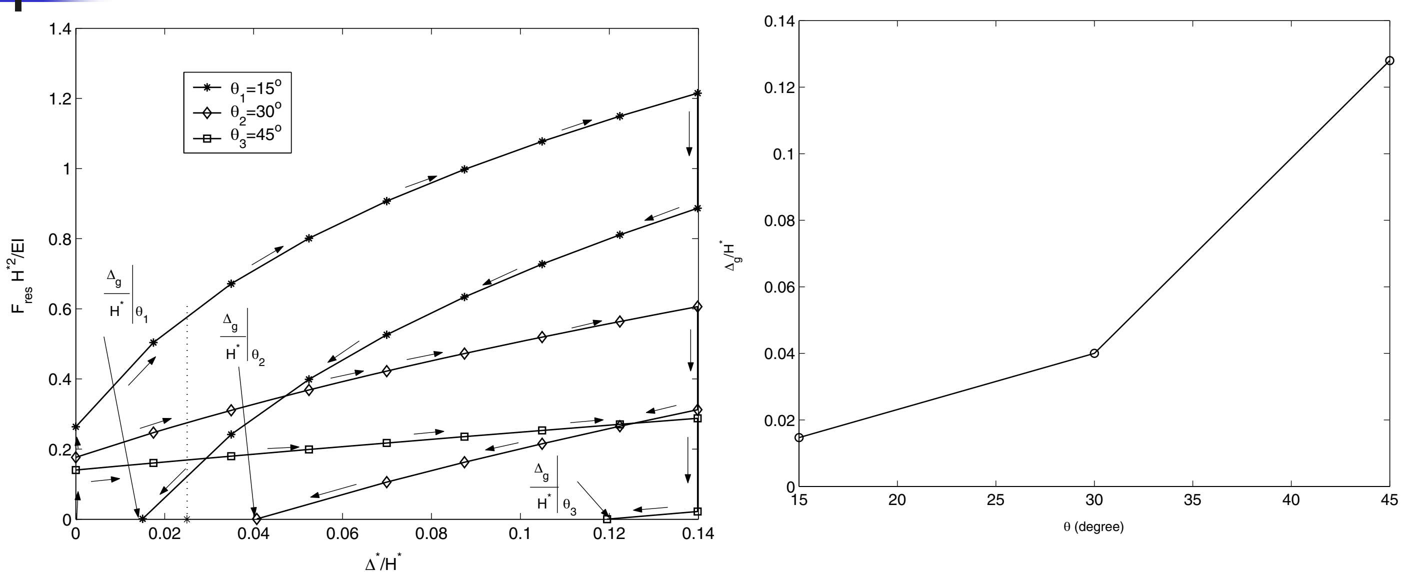

Figure 8 (a) Relationship between dimensionless contact force and dimensionless penetration depth for θ=15, 30 and 45 degrees. (Results shown are for a bristle with R_s/H^*=8.9, Δ^*_o=0, $\overline{m}$ =0.135) and (b) Relationship between Δ_g/H^* and bristle lay angle θ

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Conclusions/Summary

- The micro-moment can give rise to a delayed filament displacement as the shaft undergoes transient excursion and moves radially toward bristle pack (uploading).
- However, as the shaft returns back to its concentric position (downloading), the filament CANNOT completely recover from its deformed position and remains locked in an alternate configuration.
- Consequently, an annular gap is generated between the fiber tips and shaft surface, which promotes brush seal leakage and reduces turbo-machinery performance.

Conclusions/Summary (cont'd)

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- In general, for a given brush seal, the annular gap increases linearly as the micro moment m* is increased.

- The brush seal having a shallowest lay angle (15^o) results in the smallest annular gap, indicating that a brush seal design with shallow lay angle is least prone to hysteresis phenomenon, and can lead to improved performance.